Measurement of the differential cross sections for top quark pair production as a function of kinematic event variables in pp collisions at $\sqrt{s} = 7$ and 8 TeV

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Measurements are reported of the normalized differential cross sections for top quark pair production with respect to four kinematic event variables: the missing transverse energy; the scalar sum of the jet transverse momentum (p_{T}); the scalar sum of the p_{T} of all objects in the event; and the p_{T} of leptonically decaying W bosons from top quark decays. The data sample, collected using the CMS detector at the LHC, consists of 5.0 fb^{-1} of proton-proton collisions at $\sqrt{s} = 7$ TeV and 19.7 fb^{-1} at $\sqrt{s} = 8$ TeV. Top quark pair events containing one electron or muon are selected. The results are presented after correcting for detector effects to allow direct comparison with theoretical predictions. No significant deviations from the predictions of several standard model event simulation generators are observed.

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I. INTRODUCTION

The CERN LHC produced millions of top quark pairs ($t\bar{t}$) in 2011 and 2012. This allows for a detailed investigation of the kinematic event properties of $t\bar{t}$ production such as the missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$), the scalar sum of the jet transverse momenta (H_{T}), the scalar sum of the transverse momenta of all objects (S_{T}), and the transverse momentum (p_{T}^{W}) of leptonically decaying W bosons produced in top quark decays. These measurements can be used to verify current theoretical models, along with their implementation in simulations of $t\bar{t}$ production, and also to measure rare standard model (SM) processes such as $t\bar{t}$ production in association with a W, Z, or Higgs boson. Since top quark pair production is a major background for many searches for physics beyond the SM, it is important that the properties of $t\bar{t}$ events are well understood.

Here, we report measurements carried out using the CMS detector [1] at the LHC at two different proton-proton center-of-mass energies. The data samples used include integrated luminosities of 5.0 fb^{-1} collected in 2011 at $\sqrt{s} = 7$ TeV and 19.7 fb^{-1} from 2012 at $\sqrt{s} = 8$ TeV. The $t\bar{t}$ production cross section is measured as a function of $E_{\mathrm{T}}^{\mathrm{miss}}$, H_{T}, S_{T}, and p_{T}^{W}, corrected for detector effects, and compared with the predictions from different event generators. Differential $t\bar{t}$ cross sections have previously been measured at the Tevatron [2,3], and at the LHC [4–9]. These previous measurements study the $t\bar{t}$ production cross section as a function of the top quark kinematics and the kinematics of the $t\bar{t}$ system. The results presented here are complementary, since the $t\bar{t}$ production cross section is measured as a function of variables that do not require the reconstruction of the top quarks from their decay products.

Top quarks decay with close to 100% probability into a W boson and a bottom quark. In this article, we consider the channel in which one of the W bosons decays leptonically into a charged lepton (electron or muon) along with its associated neutrino, while the other W boson decays hadronically. This channel has a branching fraction of around 15% for direct decay to each lepton flavor and a relatively clean experimental signature, including an isolated, high-transverse-momentum lepton, large $E_{\mathrm{T}}^{\mathrm{miss}}$ from the undetected neutrino, and multiple hadronic jets. Two jets are expected to contain b hadrons from the hadronization of the b quarks produced directly in the $t \to bW$ decay, while other jets (from the hadronic W boson decay or gluon radiation) will typically contain only light and charm quarks.

II. THE CMS DETECTOR

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [1].

III. SIMULATION

For the Monte Carlo (MC) simulation of the $t\bar{t}$ signal sample the leading-order MadGraph v5.1.5.11 event

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generator [10] is used with relevant matrix elements for up to three additional partons implemented. Theoretical production cross section values of $177.3^{+4.6}_{-6.0}(\text{scale}) \pm 9.0(\text{PDF} + \alpha_S)$ pb at $\sqrt{s} = 7$ TeV, and $252.9^{+6.4}_{-8.6}(\text{scale}) \pm 11.7(\text{PDF} + \alpha_S)$ pb at $\sqrt{s} = 8$ TeV, are used for the normalization of these samples. These cross sections are calculated with the Top++2.0 program to next-to-next-to-leading order (NNLO) in perturbative QCD, including soft-gluon resummation to next-to-next-to-leading-logarithm (NNLL) order [11], and assuming a top quark mass $m_t = 172.5$ GeV. The first uncertainty comes from the independent variation of the renormalization (μ_R) and factorization (μ_F) scales, while the second one is associated with variations in the parton distribution function (PDF) and α_S, following the PDF4LHC prescription with the MSTW2008 68% CL NNLO, CT10 NNLO, and NNPDF2.3 5f FFN PDF sets [12–16].

The generated events are subsequently processed with PYTHIA v6.426 [17] for parton showering and hadronization. The PYTHIA parton shower is matched to the jets from the hard quantum chromodynamics (QCD) matrix element via the MLM prescription [18] with a transverse momentum (p_T) threshold of 20 GeV. The CMS detector response is simulated using GEANT4 [19].

Independent $t\bar{t}$ samples are also generated at both $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV with POWHEG v2 r2819 [20–22]. At 8 TeV, additional samples are generated with both MC@NLO v3.41 [23] and POWHEG v1.0 r1380 [20–22]. All of the POWHEG samples are interfaced with both PYTHIA and HERWIG v6.520 [24], whereas the MC@NLO generator is interfaced with HERWIG for parton showering. These samples, which are all generated to next-to-leading order accuracy, are used for comparison with the final results.

The most significant backgrounds to $t\bar{t}$ production are events in which a W boson is produced in association with additional jets. Other backgrounds include single top quark production, Z boson production in association with multiple jets, and QCD multijet events where hadronic activity is misidentified as a lepton. The simulation of background from W and Z boson production in association with jets is also performed using the combination of MADGRAPH and PYTHIA, with a p_T matching threshold of 10 GeV in this case. These samples are referred to as W + jets and Z + jets, respectively. Single top quark production via t- and s-channel W boson exchange [25] and with an associated on-shell W boson [26] are generated using POWHEG. The QCD multijet processes are simulated using PYTHIA. The event yields of the background processes are normalized according to their predicted production cross section values. These are from NNLO calculations for W + jets and Z + jets events [27,28], next-to-leading order calculations with NNLL corrections for single top quark events [29], and leading-order calculations for QCD multijet events [17].

Samples are generated using the CTEQ6L PDFs [30] for MADGRAPH samples, the CT10 PDFs [31] for POWHEG samples, and the CTEQ6M PDFs [30] for MC@NLO. The PYTHIA Z2 tune is used to describe the underlying event in both the MADGRAPH and POWHEG+PYTHIA samples at $\sqrt{s} = 7$ TeV, whereas the Z2* tune is used for the corresponding samples at $\sqrt{s} = 8$ TeV [32]. The underlying event in the POWHEG+HERWIG samples is described by the AUET2 tune [33], whereas the default tune is used in the MC@NLO+HERWIG sample.

The value of the top quark mass is fixed to $m_\mathrm{t} = 172.5$ GeV in all samples. In all cases, PYTHIA is used for simulating the gluon radiation and fragmentation, following the prescriptions of Ref. [34]. Additional simulated hadronic pp interactions ("pileup"), in the same or nearby beam crossings, are overlaid on each simulated event to match the high-luminosity conditions in actual data taking.

Previous measurements of differential $t\bar{t}$ production cross sections at the LHC [4,5,8] showed that several of the $t\bar{t}$ event generators considered in this analysis predict a harder top quark p_T spectrum than that observed in data. An additional simulated $t\bar{t}$ sample is considered here, where the sample produced with the MADGRAPH event generator is reweighted to improve the agreement of the top quark p_T spectrum with data.

IV. EVENT RECONSTRUCTION AND SELECTION

Parallel selection paths for the two lepton types are implemented, resulting in samples classified as electron + jets and muon + jets. The trigger for the electron + jets channel during the $\sqrt{s} = 7$ TeV data taking selects events containing an electron candidate with $p_\mathrm{T} > 25$ GeV and at least three reconstructed hadronic jets with $p_\mathrm{T} > 30$ GeV. In the $\sqrt{s} = 8$ TeV data, at least one electron candidate with $p_\mathrm{T} > 27$ GeV is required, with no additional requirement for jets. In the muon + jets channel, at least one isolated muon candidate with $p_\mathrm{T} > 24$ GeV is required at the trigger level. Each candidate event is required to contain at least one well-measured vertex [35], located within the pp luminous region in the center of CMS.

Events are reconstructed using a particle-flow (PF) technique [36,37], which combines information from all subdetectors to optimize the reconstruction and identification of individual long-lived particles.

Electron candidates are selected with a multivariate technique using calorimetry and tracking information [38]. Inputs to the discriminant include information about the calorimeter shower shape, track quality, track-shower matching, and a possible photon conversion veto. Electron candidates are required to have $E_\mathrm{T} > 30$ GeV and pseudorapidity in the range $|\eta| < 2.5$. The low-efficiency region $1.44 < |\eta| < 1.57$ between the barrel and endcap sections of the detector is excluded. Muon candidates are selected with tight requirements on track and vertex quality, and on hit multiplicity in the tracker and muon detectors [39]. These requirements suppress cosmic rays, misidentified muons, and nonprompt muons from decay of hadrons in flight. Muon candidates are required to have $p_T > 26$ GeV and $|\eta| < 2.1$.

For the lepton isolation requirement, a cone of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ is constructed around the lepton direction, where $\Delta\eta$ and $\Delta\phi$ are the differences in pseudorapidity and azimuthal angle (in radians), respectively, between the directions of the lepton and another particle. The p_T values of charged and neutral particles found in this cone are summed, excluding the lepton itself and correcting for the effects of pileup [38]. The relative isolation variable $I(\Delta R)$ is defined as the ratio of this sum to the lepton p_T. Lepton candidates are selected if they satisfy $I(0.3) < 0.1$ for electrons, and $I(0.4) < 0.12$ for muons.

Reconstructed particles are clustered into jets using the anti-k_T algorithm [40] with a distance parameter of 0.5. The measured p_T of each jet is corrected [41] for known variations in the jet energy response as a function of the measured jet η and p_T. The jet energy is also corrected for the extra energy deposition from pileup interactions [42,43]. Jets are required to pass loose identification requirements to remove calorimeter noise [44]. Any such jet whose direction is less than $\Delta R = 0.3$ from the identified lepton direction is removed. For the identification of b quark jets ("b tagging"), a "combined secondary vertex" algorithm [45] is used, taking into account the reconstructed secondary vertices and track-based lifetime information. The b tagging threshold is chosen to give an acceptance of 1% for light-quark and gluon jets with a tagging efficiency of 65% for b quark jets.

The final selection requires exactly one high-p_T, isolated electron or muon. Events are vetoed if they contain an additional lepton candidate satisfying either of the following criteria: an electron with $p_T > 20$ GeV, $|\eta| < 2.5$, and $I(0.3) < 0.15$; or a muon, with looser requirements on hit multiplicity, and with $p_T > 10$ GeV, $|\eta| < 2.5$, and $I(0.4) < 0.2$. The event must have at least four jets with $p_T > 30$ GeV, of which at least two are tagged as containing b hadrons.

After the final selection, 26 290 data events are found at $\sqrt{s} = 7$ TeV, and 153 223 at $\sqrt{s} = 8$ TeV. The $t\bar{t}$ contribution to these event samples, as estimated from simulation, is about 92%. The fraction of true signal events in the samples is 78%. Misidentified all-hadronic or dileptonic $t\bar{t}$ events, and events containing tau leptons among the $t\bar{t}$ decay products, comprise 14% of the samples. The remaining events are approximately 4% single top quark events, 2% $W/Z+$jets events, and 2% QCD multijet events. The efficiency for signal events to satisfy the final selection criteria is about 8%, as determined from simulation.

V. CROSS SECTION MEASUREMENTS

We study the normalized $t\bar{t}$ differential production cross section as a function of four kinematic event variables: E_T^{miss}, H_T, S_T, and p_T^W.

The variable E_T^{miss} is the magnitude of the missing transverse momentum vector $\vec{p}_T^{\text{miss}}$, which is defined as the projection on the plane perpendicular to the beams of the negative vector sum of the momenta of all PF candidates in the event:

$$E_T^{\text{miss}} = \left[\left(-\sum_i p_x^i\right)^2 + \left(-\sum_i p_y^i\right)^2\right]^{\frac{1}{2}},$$

where p_x^i and p_y^i are the x and y momentum components of the ith candidate, and the sums extend over all PF candidates. The measured E_T^{miss} is corrected for pileup and nonuniformities in response as a function of ϕ [46].

The variable H_T is defined as the scalar sum of the transverse momenta of all jets in the event,

$$H_T = \sum_{\text{all jets}} p_T^{\text{jet}},$$

where the sum extends over all jets having $p_T > 20$ GeV and $|\eta| < 2.5$.

The variable S_T is the scalar sum of H_T, E_T^{miss}, and the p_T of the identified lepton,

$$S_T = H_T + E_T^{\text{miss}} + p_T^{\text{lepton}}.$$

Finally, p_T^W is the magnitude of the transverse momentum of the leptonically decaying W boson, which is derived from the momentum of the isolated lepton and $\vec{p}_T^{\text{miss}}$

$$p_T^W = \sqrt{(p_x^{\text{lepton}} + p_x^{\text{miss}})^2 + (p_y^{\text{lepton}} + p_y^{\text{miss}})^2},$$

where p_x^{lepton} and p_y^{lepton} are the transverse components of $\vec{p}^{\text{lepton}}$, and p_x^{miss} and p_y^{miss} are the transverse components of $\vec{p}_T^{\text{miss}}$.

Figures 1 and 2 show the observed distributions of E_T^{miss}, H_T, S_T, and p_T^W, in the $\sqrt{s} = 8$ TeV data samples, compared to the sum of the corresponding signal and background distributions from simulation.

For simulated $t\bar{t}$ signal events, these four kinematic variables are also calculated using the momenta of particles in the event, before the simulation of the detector response. We refer to the quantities calculated in this way as the generated variables. The generated value of E_T^{miss} is the magnitude of the vector sum of the p_T of all neutrinos in the event. The long-lived particles in the event are clustered into jets in the same way as the reconstructed particles. The generated value of H_T is the sum of the magnitudes of the p_T of these jets with $p_T > 20$ GeV and $|\eta| < 2.5$. The generated values of S_T and p_T^W are calculated in the same way as the corresponding reconstructed variables, using the $\vec{p}_T$ of the charged lepton from the leptonic decay of a W boson coming from $t \to bW$ decay.

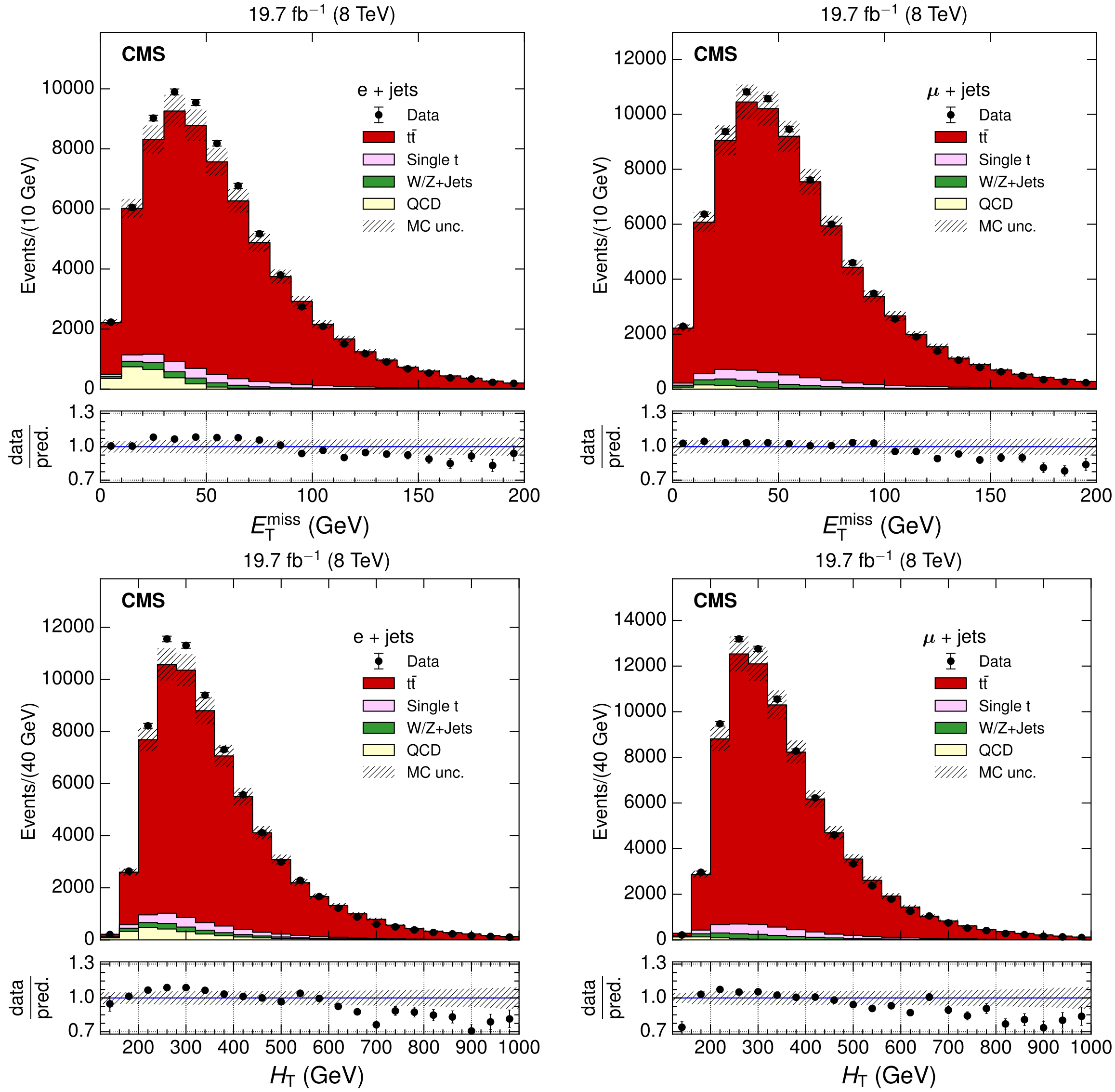

FIG. 1. The observed distributions of $E_{\mathrm{T}}^{\mathrm{miss}}$ (top) and H_{T} (bottom) in the $\sqrt{s} = 8$ TeV electron + jets (left) and muon + jets (right) data samples, compared to predictions from simulation. The points are the data histograms, with the vertical bars showing the statistical uncertainty, and the predictions from the simulation are the solid histograms. The shaded region shows the uncertainty in the values from simulation. These include contributions from the statistical uncertainty and the uncertainty in the $t\bar{t}$ cross section. The lower plots show the ratio of the number of events from data and the prediction from the MC simulation.

The choice of bin widths for this measurement is optimized separately for each kinematic event variable to minimize the migration between bins. This optimization is based on three criteria: (i) of the simulated signal events for which the value of the generated variable falls in the bin, at least 50% are required to have the reconstructed variable in the same bin (this is sensitive to migration of events out of the bin); (ii) of the simulated signal events for which the value of the reconstructed variable falls in the bin, at least 50% are required to have the generated variable in the same bin (this is sensitive to migration of events into the bin); (iii) the number of reconstructed simulation events in a bin is required to be more than 100. These criteria ensure that bin-to-bin migrations are kept small, while allowing a differential cross section measurement with reasonable granularity.

The number of $t\bar{t}$ events in each bin of each kinematic event variable, and in each channel, is obtained by subtracting the expected contributions of background processes from data. The contributions of single top quark, and W or Z boson plus jet events are estimated from simulation.

In the case of the QCD multijet background, the contribution is estimated from data using a control region where the selection criteria are modified to enrich the contribution of QCD multijet events. In the electron + jets

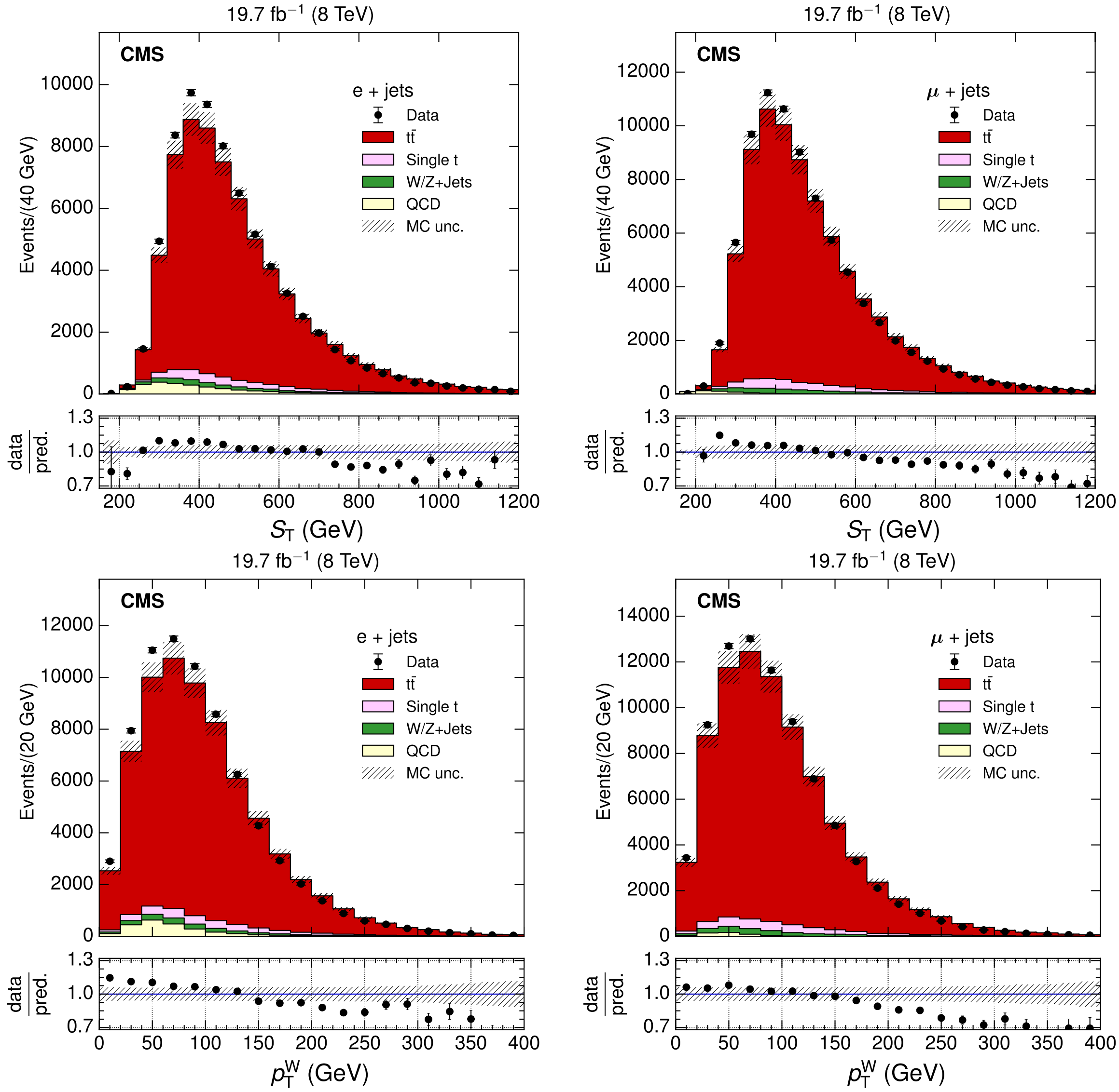

FIG. 2. The observed distributions of S_T (top) and p_T^W (bottom) in the $\sqrt{s} = 8$ TeV electron + jets (left) and muon + jets (right) data samples, compared to predictions from simulation. The points are the data histograms, with the vertical bars showing the statistical uncertainty, and the predictions from the simulation are the solid histograms. The shaded region shows the uncertainty in the values from simulation. These include contributions from the statistical uncertainty and the uncertainty in the $t\bar{t}$ cross section. The lower plots show the ratio of the number of events from data and the prediction from the MC simulation.

channel, the control region is obtained by inverting the photon conversion veto on the electron. In addition to this, the number of b-tagged jets is required to be exactly zero. The small contamination of $t\bar{t}$, single top, $W +$ jets, and $Z +$ jets events in this control region, as estimated from simulation, is subtracted from the data. Then, the ratio of simulated QCD multijet events in the control region and the signal region is used to scale the normalization of the data-driven QCD multijet estimate from the control region to the signal region in the data. The control region in the muon + jets channel is obtained by inverting the isolation criterion on the muon in the selected events, and by requiring exactly zero b-tagged jets. The jet selection criterion is also modified, requiring at least three jets. The same procedure is then followed to estimate the contribution of QCD mulitjet events in the muon + jets signal region.

The number of $t\bar{t}$ events from data in each bin is then corrected for the small fractions of dileptonic, all-hadronic, and tau $t\bar{t}$ events in the final sample, as determined from simulation, and for experimental effects, such as detector resolution, acceptance, and efficiency. This correction is performed by constructing a response matrix that maps the generated values to the reconstructed values for the four kinematic variables in the simulated $t\bar{t}$ signal events. The response matrix is constructed using the MadGraph $t\bar{t}$ sample. This matrix is then inverted, using regularized singular-value decomposition [47] in the RooUnfold [48] software framework. Since we impose no requirements on the generated events, the procedure corrects to the full signal phase space.

The fully corrected numbers of $t\bar{t}$ events in the electron + jets and muon + jets channels yield consistent results. These are then added and used to calculate the normalized $t\bar{t}$ differential production cross section with respect to each kinematic event variable, X, using

$$\frac{1}{\sigma}\frac{d\sigma_j}{dX} = \frac{1}{N}\frac{x_j}{\Delta_j^X}, \tag{1}$$

where x_j represents the number of unfolded signal events in bin j, Δ_j^X is the width of bin j, σ is the total $t\bar{t}$ production cross section, and $N = \sum_i x_i$ is the total number of unfolded signal events.

VI. SYSTEMATIC UNCERTAINTIES

The systematic uncertainties in the experimental and theoretical input quantities are evaluated and propagated to the final results, taking correlations into account. Since the final result is normalized to the total number of events, the effect of uncertainties that are correlated across all bins is negligible. As such, only uncertainties that affect the shape of the measured distributions are significant.

The uncertainty coming from the choice of renormalization and factorization scales in the physics modeling of $t\bar{t}$ events is determined by producing two additional simulated event samples. These samples are generated with both scales simultaneously varied by a factor of two up or down from their default values equal to the Q of the hard process in the event; Q is defined via $Q^2 = {m_t}^2 + \sum p_{\mathrm{T}}^2$, where the sum is over all additional final-state partons in the matrix element. The effect of varying the renormalization and factorization scales in the W + jets and Z + jets samples is also considered to determine the uncertainty in the shape of this background. The uncertainty arising from the choice of parton shower matching threshold in the event generation is determined in a similar fashion, using additional samples in which the threshold is varied up or down. Uncertainties from the modeling of the hadronization are evaluated by comparing POWHEG v1 simulated samples with two different hadron shower generators (PYTHIA and HERWIG). The uncertainty owing to the choice of the PDF is determined by reweighting the simulated events and repeating the analysis using the 44 CTEQ6L PDF error sets [30]. The maximum variation is taken as the uncertainty. Simulated samples with the top quark mass varied by ± 1 GeV, which corresponds to the precision of the measured top quark mass [49], are generated to evaluate the effect of the uncertainty in this parameter. The effect of reweighting the top quark p_{T} spectrum in simulation, as described in Sec. III, is found to have a negligible effect for low values of the kinematic event variables, and increases to 3%–7% for the highest values.

Other uncertainties are associated with imperfect understanding of efficiencies, resolutions, and scales describing the detector response. The uncertainty arising from each source is estimated, and the analysis repeated with each corresponding parameter varied within its uncertainty.

The efficiencies and associated uncertainties for triggering and lepton identification are determined from data by a tag-and-probe method [50]. The probabilities for identifying and misidentifying b jets in the simulation are compared to those measured in data, and the resulting correction factors and their uncertainties are determined as a function of jet energy and quark flavor. The uncertainties in the correction factors are typically 2%.

The uncertainty in the jet energy scale (JES) is determined as a function of the jet p_{T} and η [41], and an uncertainty of 10% is included in the jet energy resolution (JER) [41]. The effect of this limited knowledge of the JES and JER is determined by varying the JES and JER in the simulated samples within their uncertainties. The uncertainty in the JES and JER, as well as uncertainties in the electron, photon, tau, and muon energy scale, are propagated into the calculation of $E_{\mathrm{T}}^{\mathrm{miss}}$. The uncertainty in the electron and photon energy scale is 0.6% in the barrel, and 1.5% in the endcap [38]. The uncertainty in the tau lepton energy scale is estimated to be $\pm 3\%$ [51], while the effect of the uncertainty in the muon momentum measurement is found to be negligible. A 10% uncertainty is assigned to the

TABLE I. Typical relative systematic uncertainties in percent (median values) in the normalized $t\bar{t}$ differential cross section measurement as a function of the four kinematic event variables at a center-of-mass energy of 8 TeV (combination of electron and muon channels). Typical values of the total systematic uncertainty are also shown.

	Relative (%)			
Uncertainty source	$E_{\mathrm{T}}^{\mathrm{miss}}$	H_{T}	S_{T}	p_{T}^{W}
Fact./Renorm. scales and matching threshold	7.6	4.0	2.6	3.3
Hadronization	4.3	5.0	8.5	3.0
PDF	0.5	0.6	0.6	0.4
Top quark mass	0.4	0.7	0.8	0.3
Top quark p_{T} reweighting	1.4	0.9	0.6	0.6
Lepton trigger efficiency & selection	<0.1	<0.1	<0.1	<0.1
b tagging	0.3	0.1	0.3	<0.1
Jet energy scale	0.3	0.2	0.3	<0.1
Jet energy resolution	<0.1	<0.1	<0.1	<0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.2	...	< 0.1	0.1
Pileup	0.4	<0.1	0.1	0.2
Background normalization	2.6	1.0	2.1	1.4
QCD shape	0.4	0.2	0.5	0.4
Total	9.9	8.6	9.5	4.4

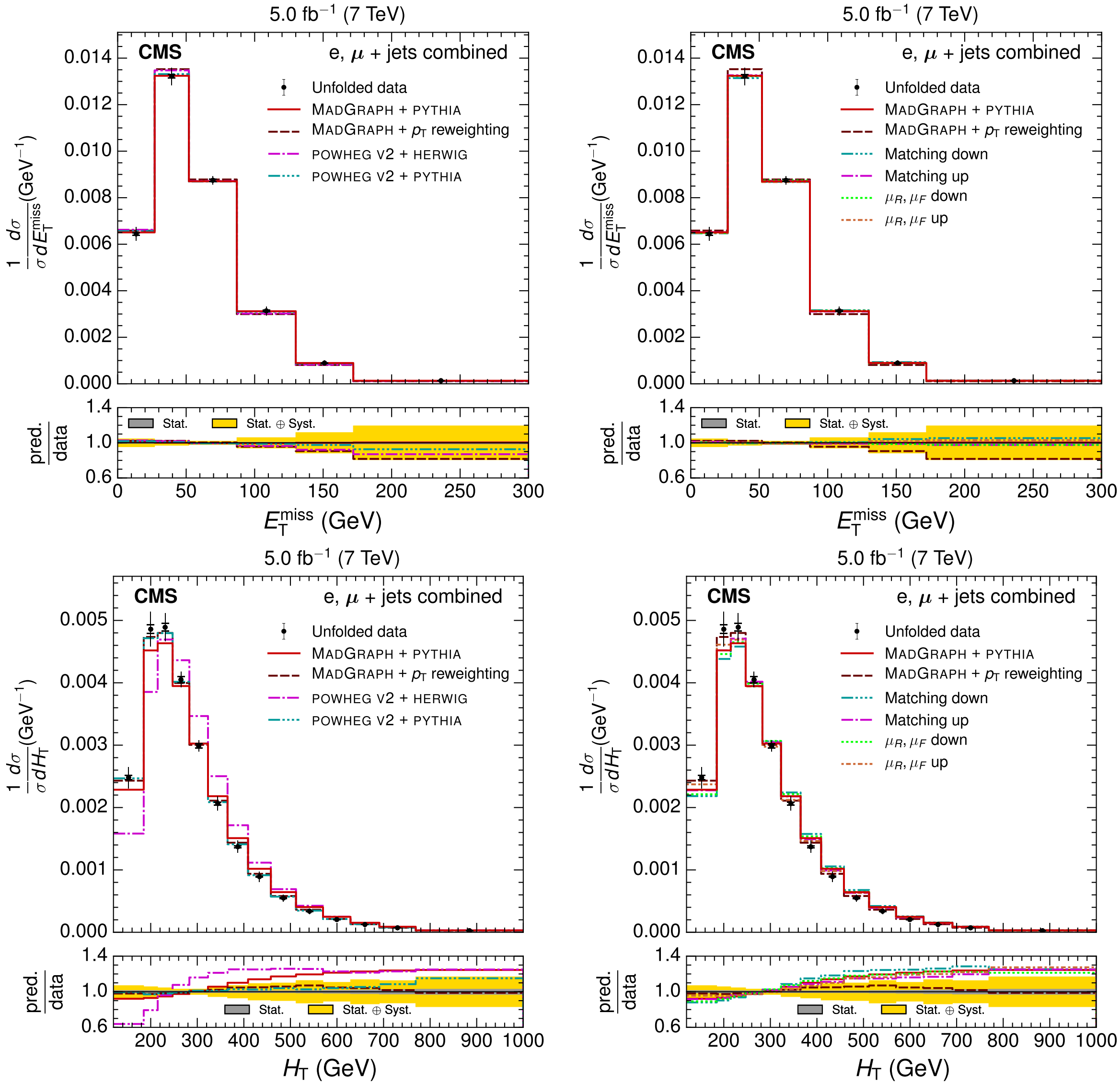

FIG. 3. Normalized E_T^{miss} (top) and H_T (bottom) differential $t\bar{t}$ cross sections from the combined electron and muon data at $\sqrt{s} = 7$ TeV. The vertical bars on the data points represent the statistical and systematic uncertainties added in quadrature. The inner section of the vertical bars, denoted by the tick marks, show the statistical uncertainty. Left: comparison with different simulation event generators: MadGraph+pythia (both the default and after reweighting the top quark p_T spectrum), powheg v2+herwig, and powheg v2+pythia. Right: comparison with predictions from the MadGraph+pythia event generator found by varying the matching threshold and renormalization scales (μ_R, μ_F) up and down by a factor of 2. The lower plots show the ratio of the predictions to the data, with the statistical and total uncertainties in the ratios indicated by the two shaded bands.

estimate of the nonclustered energy used in the calculation of E_T^{miss} [46].

The effect of the uncertainty in the level of pileup is estimated by varying the inelastic pp cross section used in the simulation by $\pm 5\%$ [52].

The uncertainty in the normalization of the background is determined by varying the normalization of the single top, $W+$jets, and $Z+$jets processes by $\pm 30\%$, and the QCD multijet processes by $\pm 100\%$. The uncertainty in the shape of the QCD multijet distribution in the electron channel is estimated by using an alternative control region in data to determine the contribution of QCD multijet events. This uncertainty is found to have a negligible effect.

The dominant systematic effects are caused by the uncertainties in the modeling of the hadronization and the $t\bar{t}$ signal. For illustrative purposes, typical systematic uncertainties in the $\sqrt{s} = 8$ TeV results coming from each of the sources described above are presented in Table I. The values shown for each kinematic event variable are the median uncertainties over all of the bins for that variable.

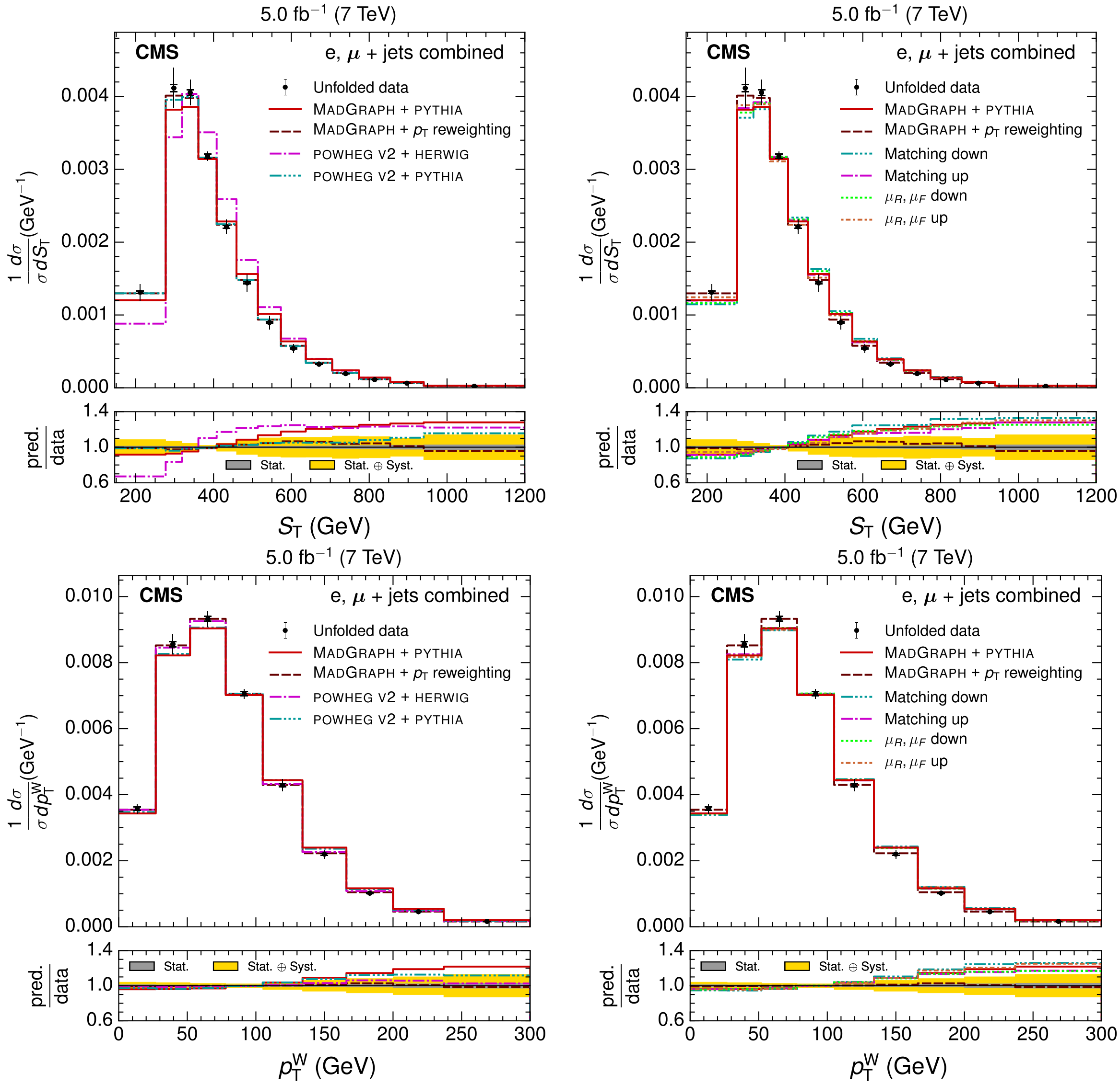

FIG. 4. Normalized S_T (top) and p_T^W (bottom) differential $t\bar{t}$ cross sections from combined electron and muon data at $\sqrt{s} = 7$ TeV. The vertical bars on the data points represent the statistical and systematic uncertainties added in quadrature. The inner section of the vertical bars, denoted by the tick marks, show the statistical uncertainty. Left: comparison with different simulation event generators: MADGRAPH+PYTHIA (both the default and after reweighting the top quark p_T spectrum), POWHEG V2+HERWIG, and POWHEG V2+PYTHIA. Right: comparison with predictions from the MADGRAPH+PYTHIA event generator found by varying the matching threshold and renormalization scales (μ_R, μ_F) up and down by a factor of 2. The lower plots show the ratio of the predictions to the data, with the statistical and total uncertainties in the ratios indicated by the two shaded bands.

VII. RESULTS

The normalized differential $t\bar{t}$ cross sections as a function of each of the kinematic event variables are shown in Figs. 3 and 4 for the $\sqrt{s} = 7$ TeV data, and in Figs. 5 and 6 for the $\sqrt{s} = 8$ TeV data. The results are also presented in Tables II–IX of the Appendix.

The data distributions in the figures are compared with the predictions from the event generators in the left-hand plots: MADGRAPH and POWHEG V2 with two different hadron shower generators, PYTHIA and HERWIG. For the $\sqrt{s} = 8$ TeV results, the predictions from the MC@NLO and POWHEG V1 generators are also shown. The effect on the predicted distributions from varying the modeling parameters (the matching threshold and renormalization scale Q^2) up and down by a factor of 2 for the MADGRAPH event generator is shown in the right-hand plots for the two MADGRAPH simulations. The uncertainties shown by the vertical bars on the points in the figures and given in the tables include both the statistical uncertainties and those resulting from the unfolding procedure.

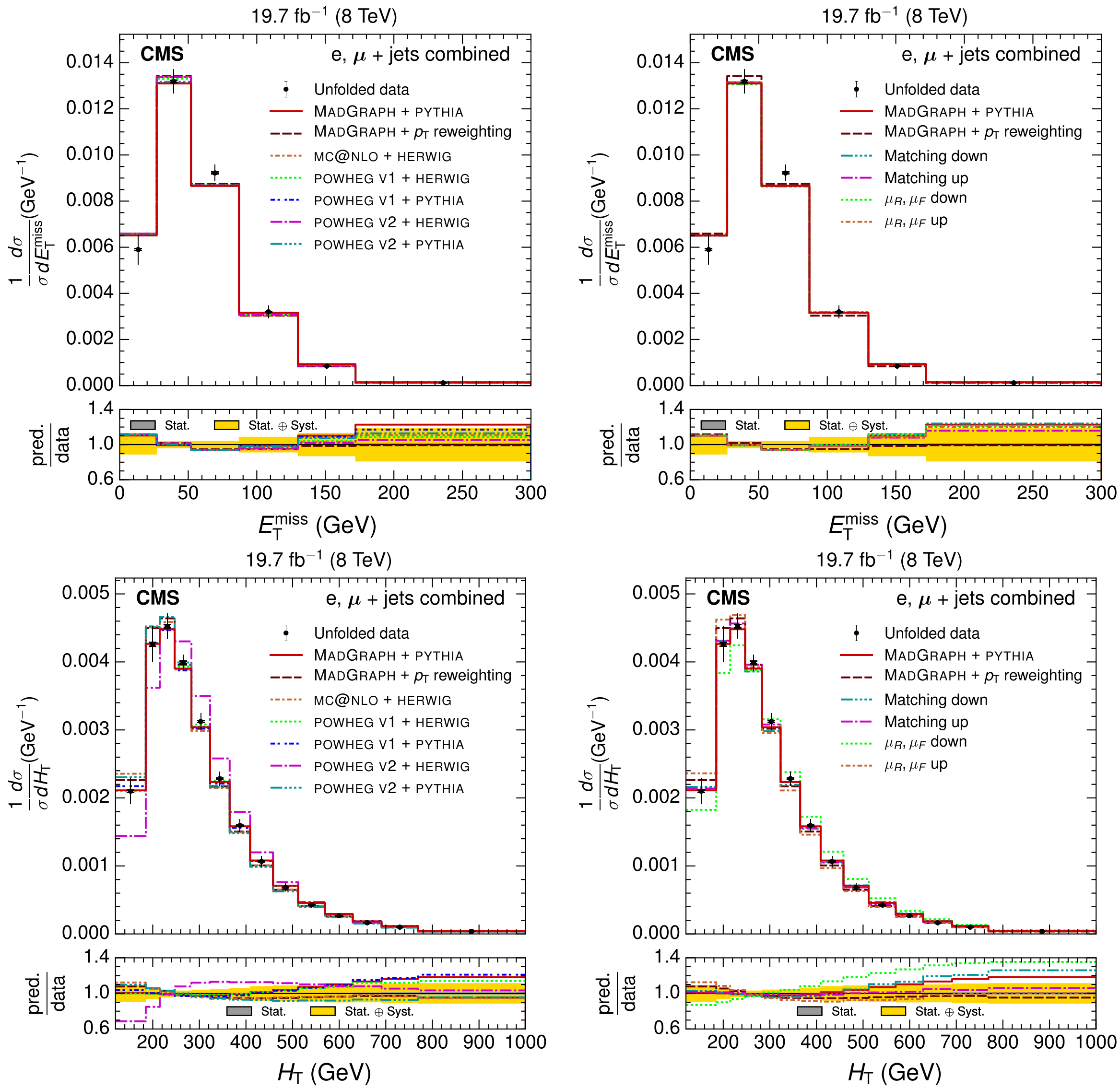

FIG. 5. Normalized E_T^{miss} (top) and H_T (bottom) differential $t\bar{t}$ cross sections from combined electron and muon data at $\sqrt{s} = 8$ TeV. The vertical bars on the data points represent the statistical and systematic uncertainties added in quadrature. The inner section of the vertical bars, denoted by the tick marks, show the statistical uncertainty. Left: comparison with different simulation event generators: MadGraph+pythia (both the default and after reweighting the top quark p_T spectrum), MC@NLO+HERWIG, POWHEG V1+HERWIG, POWHEG V1+PYTHIA, POWHEG V2+HERWIG, and POWHEG V2+PYTHIA. Right: comparison with predictions from the PYTHIA event generator found by varying the matching threshold and renormalization scales (μ_R, μ_F) up and down by a factor of 2. The lower plots show the ratio of the predictions to the data, with the statistical and total uncertainties in the ratios indicated by the two shaded bands.

The measurements at $\sqrt{s} = 7$ TeV are well described by all the event generators in the distribution of E_T^{miss}. For S_T, p_T^W, and H_T, the event generators predict a somewhat harder spectrum than seen in data. However, the POWHEG V2+PYTHIA event generator provides a reasonable description of the H_T and S_T differential cross sections.

The results at $\sqrt{s} = 8$ TeV are generally well described by the MC@NLO and the POWHEG V2+PYTHIA event generators. The POWHEG V2+HERWIG event generator describes the E_T^{miss} and p_T^W distributions well. However, for H_T and S_T this event generator predicts a harder spectrum than seen in data, at both center-of-mass energies.

The MadGraph event generator generally predicts a harder spectrum than seen in data for all variables. The variations in matching threshold and Q^2 in the MadGraph event generator are not sufficient to explain this difference between the prediction and data. However, the MadGraph event generator provides a good description of the data after

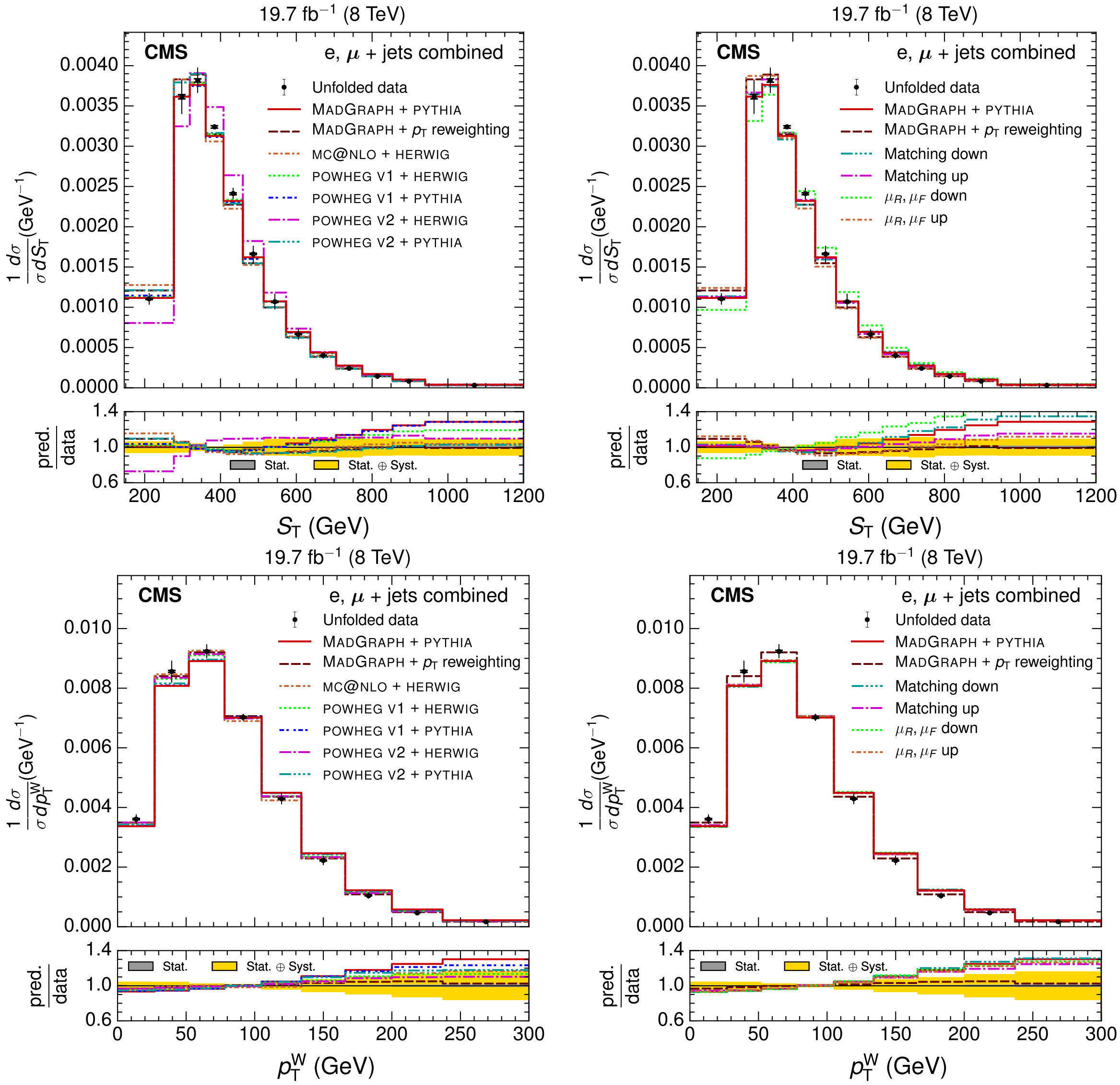

FIG. 6. Normalized S_T (top) and p_T^W (bottom) differential $t\bar{t}$ cross sections from combined electron and muon data at $\sqrt{s} = 8$ TeV. The vertical bars on the data points represent the statistical and systematic uncertainties added in quadrature. The inner section of the vertical bars, denoted by the tick marks, show the statistical uncertainty. Left: comparison with different simulation event generators: MADGRAPH+PYTHIA (both the default and after reweighting the top quark p_T spectrum), MC@NLO+HERWIG, POWHEG V1+HERWIG, POWHEG V1+PYTHIA, POWHEG V2+HERWIG, and POWHEG V2+PYTHIA. Right: comparison with predictions from the MADGRAPH+PYTHIA event generator found by varying the matching threshold and renormalization scales (μ_R, μ_F) up and down by a factor of 2. The lower plots show the ratio of the predictions to the data, with the statistical and total uncertainties in the ratios indicated by the two shaded bands.

reweighting the top quark p_T spectrum, as described in Sec. III. The prediction obtained from the MADGRAPH event generator after the reweighting is shown on all the plots.

VIII. SUMMARY

A measurement of the normalized differential cross section of top quark pair production with respect to the four kinematic event variables E_T^{miss}, H_T, S_T, and p_T^W has been performed in pp collisions at a center-of-mass energy of 7 TeV using 5.0 fb^{-1} and at 8 TeV using 19.7 fb^{-1} of data collected by the CMS experiment.

This study confirms previous CMS findings that the observed top quark p_T spectrum is softer than predicted by the MADGRAPH, POWHEG, and MC@NLO event generators, but otherwise there is broad consistency between the MC event generators and observation. This result provides confidence in the description of $t\bar{t}$ production in the SM and its implementation in the most frequently used simulation packages.

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APPENDIX: ADDITIONAL TABLES

The measured values of the $t\bar{t}$ differential cross sections as a function of $E_{\mathrm{T}}^{\mathrm{miss}}$, H_{T}, S_{T}, and p_{T}^{W} for $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV are given in the Tables II–IX below, along with their statistical, systematic, and total uncertainties.

TABLE II. Normalized $t\bar{t}$ differential cross section measurements with respect to the $E_{\mathrm{T}}^{\mathrm{miss}}$ variable at a center-of-mass energy of 7 TeV (combination of electron and muon channels). The rightmost three columns show the relative uncertainties on the measured values, in percent. The statistical and systematic uncertainties are listed separately, and are combined in quadrature to give the overall relative uncertainty.

$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	$1/\sigma\, d\sigma/dE_{\mathrm{T}}^{\mathrm{miss}}$ (GeV^{-1})	±stat (%)	±syst (%)	Relative uncertainty (%)
0–27	6.44×10^{-3}	0.83	4.5	4.6
27–52	1.32×10^{-2}	0.60	2.8	2.9
52–87	8.75×10^{-3}	0.58	1.9	2.0
87–130	3.14×10^{-3}	0.80	6.0	6.0
130–172	8.93×10^{-4}	1.1	12	12
172–300	1.32×10^{-4}	1.4	19	19

TABLE III. Normalized $t\bar{t}$ differential cross section measurements with respect to the H_{T} variable at a center-of-mass energy of 7 TeV (combination of electron and muon channels). The rightmost three columns show the relative uncertainties on the measured values, in percent. The statistical and systematic uncertainties are listed separately, and are combined in quadrature to give the overall relative uncertainty.

H_{T} (GeV)	$1/\sigma\, d\sigma/dH_{\mathrm{T}}$ (GeV^{-1})	±stat (%)	±syst (%)	Relative uncertainty (%)
120–185	2.48×10^{-3}	1.5	6.8	6.9
185–215	4.86×10^{-3}	1.4	5.5	5.7
215–247	4.89×10^{-3}	1.3	4.4	4.6
247–283	4.05×10^{-3}	1.2	2.8	3.1
283–323	2.99×10^{-3}	1.1	2.9	3.1
323–365	2.06×10^{-3}	1.1	5.4	5.6
365–409	1.37×10^{-3}	1.1	7.0	7.1
409–458	8.93×10^{-4}	1.1	9.3	9.4
458–512	5.49×10^{-4}	1.2	9.9	10
512–570	3.38×10^{-4}	1.4	13	13
570–629	2.04×10^{-4}	1.8	10	11
629–691	1.25×10^{-4}	2.2	14	14
691–769	7.20×10^{-5}	2.7	12	13
769–1000	2.51×10^{-5}	3.0	17	17

TABLE IV. Normalized $t\bar{t}$ differential cross section measurements with respect to the S_T variable at a center-of-mass energy of 7 TeV (combination of electron and muon channels). The rightmost three columns show the relative uncertainties on the measured values, in percent. The statistical and systematic uncertainties are listed separately, and are combined in quadrature to give the overall relative uncertainty.

S_T (GeV)	$1/\sigma\, d\sigma/dS_T$ (GeV^{-1})	±stat (%)	±syst (%)	Relative uncertainty (%)
146–277	1.31×10^{-3}	1.2	8.4	8.5
277–319	4.12×10^{-3}	1.1	6.7	6.8
319–361	4.05×10^{-3}	1.0	4.2	4.3
361–408	3.18×10^{-3}	0.91	1.8	2.0
408–459	2.21×10^{-3}	0.93	4.5	4.6
459–514	1.44×10^{-3}	1.0	8.1	8.2
514–573	8.96×10^{-4}	1.1	10	11
573–637	5.42×10^{-4}	1.2	11	11
637–705	3.25×10^{-4}	1.3	11	11
705–774	1.95×10^{-4}	1.6	12	13
774–854	1.13×10^{-4}	1.9	12	12
854–940	6.32×10^{-5}	2.3	10	10
940–1200	2.26×10^{-5}	2.7	14	14

TABLE V. Normalized $t\bar{t}$ differential cross section measurements with respect to the p_T^W variable at a center-of-mass energy of 7 TeV (combination of electron and muon channels). The rightmost three columns show the relative uncertainties on the measured values, in percent. The statistical and systematic uncertainties are listed separately, and are combined in quadrature to give the overall relative uncertainty.

p_T^W (GeV)	$1/\sigma\, d\sigma/dp_T^W$ (GeV^{-1})	±stat (%)	±syst (%)	Relative uncertainty (%)
0–27	3.58×10^{-3}	1.3	3.8	4.1
27–52	8.56×10^{-3}	0.96	3.4	3.6
52–78	9.33×10^{-3}	0.81	2.5	2.6
78–105	7.06×10^{-3}	0.96	1.9	2.1
105–134	4.28×10^{-3}	1.2	4.1	4.2
134–166	2.20×10^{-3}	1.3	6.1	6.2
166–200	1.02×10^{-3}	1.6	8.0	8.1
200–237	4.56×10^{-4}	2.2	9.9	10
237–300	1.63×10^{-4}	2.9	13	13

TABLE VI. Normalized $t\bar{t}$ differential cross section measurements with respect to the E_T^{miss} variable at a center-of-mass energy of 8 TeV (combination of electron and muon channels). The rightmost three columns show the relative uncertainties on the measured values, in percent. The statistical and systematic uncertainties are listed separately, and are combined in quadrature to give the overall relative uncertainty.

E_T^{miss} (GeV)	$1/\sigma\, d\sigma/dE_T^{\mathrm{miss}}$ (GeV^{-1})	±stat (%)	±syst (%)	Relative uncertainty (%)
0–27	5.90×10^{-3}	0.59	11	11
27–52	1.32×10^{-2}	0.36	3.9	3.9
52–87	9.22×10^{-3}	0.40	3.9	3.9
87–130	3.20×10^{-3}	0.55	8.6	8.7
130–172	8.46×10^{-4}	0.81	13	13
172–300	1.18×10^{-4}	1.3	19	19

TABLE VII. Normalized $t\bar{t}$ differential cross section measurements with respect to the H_T variable at a center-of-mass energy of 8 TeV (combination of electron and muon channels). The rightmost three columns show the relative uncertainties on the measured values, in percent. The statistical and systematic uncertainties are listed separately, and are combined in quadrature to give the overall relative uncertainty.

H_T (GeV)	$1/\sigma\, d\sigma/dH_T$ (GeV^{-1})	±stat (%)	±syst (%)	Relative uncertainty (%)
120–185	2.10×10^{-3}	0.68	9.1	9.1
185–215	4.26×10^{-3}	0.65	6.1	6.2
215–247	4.52×10^{-3}	0.57	4.1	4.1
247–283	3.99×10^{-3}	0.50	2.9	3.0
283–323	3.12×10^{-3}	0.46	4.0	4.0
323–365	2.28×10^{-3}	0.44	4.5	4.6
365–409	1.60×10^{-3}	0.44	5.8	5.8
409–458	1.07×10^{-3}	0.43	7.9	7.9
458–512	6.83×10^{-4}	0.45	8.6	8.6
512–570	4.26×10^{-4}	0.51	9.0	9.0
570–629	2.66×10^{-4}	0.65	9.9	9.9
629–691	1.64×10^{-4}	0.82	9.7	9.7
691–769	9.93×10^{-5}	0.99	11	11
769–1000	3.78×10^{-5}	1.1	11	11

TABLE VIII. Normalized $t\bar{t}$ differential cross section measurements with respect to the S_T variable at a center-of-mass energy of 8 TeV (combination of electron and muon channels). The rightmost three columns show the relative uncertainties on the measured values, in percent. The statistical and systematic uncertainties are listed separately, and are combined in quadrature to give the overall relative uncertainty.

S_T (GeV)	$1/\sigma\, d\sigma/dS_T$ (GeV^{-1})	±stat (%)	±syst (%)	Relative uncertainty (%)
146–277	1.10×10^{-3}	0.84	6.3	6.3
277–319	3.61×10^{-3}	0.71	5.8	5.9
319–361	3.82×10^{-3}	0.54	4.1	4.1
361–408	3.24×10^{-3}	0.46	0.80	0.92
408–459	2.41×10^{-3}	0.48	2.8	2.9
459–514	1.66×10^{-3}	0.57	6.1	6.1
514–573	1.07×10^{-3}	0.69	9.0	9.1
573–637	6.65×10^{-4}	0.74	9.6	9.6
637–705	4.03×10^{-4}	0.71	10	10
705–774	2.43×10^{-4}	0.73	11	11
774–854	1.44×10^{-4}	0.88	9.3	9.4
854–940	8.21×10^{-5}	1.2	8.9	9.0
940–1200	3.15×10^{-5}	1.5	9.2	9.4

TABLE IX. Normalized $t\bar{t}$ differential cross section measurements with respect to the p_T^W variable at a center-of-mass energy of 8 TeV (combination of electron and muon channels). The rightmost three columns show the relative uncertainties on the measured values, in percent. The statistical and systematic uncertainties are listed separately, and are combined in quadrature to give the overall relative uncertainty.

p_T^W (GeV)	$1/\sigma\, d\sigma/dp_T^W$ (GeV^{-1})	±stat (%)	±syst (%)	Relative uncertainty (%)
0–27	3.61×10^{-3}	0.54	4.4	4.4
27–52	8.56×10^{-3}	0.40	4.3	4.3
52–78	9.23×10^{-3}	0.34	2.5	2.5
78–105	7.02×10^{-3}	0.40	1.6	1.6
105–134	4.29×10^{-3}	0.50	4.3	4.3
134–166	2.22×10^{-3}	0.55	7.1	7.1
166–200	1.04×10^{-3}	0.67	9.6	9.6
200–237	4.66×10^{-4}	0.94	13	13
237–300	1.69×10^{-4}	1.2	16	16

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